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Emissions Characterization in the Contained Underground Demilitarization Laboratory at the Nevada Test Site

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EMISSIONS CHARACTERIZATION IN THE CONTAINED UNDERGROUND DEMILITARIZATION LABORATORY AT THE NEVADA TEST SITE

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ABSTRACT

The US Departments of Defense and Energy (DoD and DOE) have established a Joint Demilitarization Technology (JDT) Program to demonstrate and validate technologies for resource recovery and recycling, as well as alternative destruction or treatment technologies as appropriate to specific conventional stockpile segments. X-Tunnel at the DOE's Nevada Test Site is a facility for emissions characterization from detonation of conventional munitions and burning of rocket motors. We conducted seven detonations of M107, high explosive 155-mm projectiles, four from December 1996 through March 1997 and three during July and August 1999. We also completed three burns of rocket motors from May through June 1997. Standard DoD procedures for open detonation(OD) of ordnance and open burn (OB) of rocket motors were followed in order to establish baseline emissions. Measurements inside the chamber included pressures, temperatures, relative humidity and gas concentrations. Grab samples were collected for gas, organic, metal and particulate analyses. Results and implications for developing alternative destruction techniques will be presented.

Introduction

The Joint Demilitarization Technology Program, directed by Mr. James Q. Wheeler of the Defense Ammunition Center, developed the X-Tunnel facility at NTS to provide a unique capability to characterize emissions from contained, full-scale detonation and burn procedures currently used for disposal of conventional munitions and rocket motors. A series of experiments begun in 1996 have demonstrated the ability to replicate the procedures and obtain data that can be used to evaluate and improve destructive disposal operations.

This program fulfills DoD directives to develop safe, efficient, environmentally acceptable demilitarization processes for the resource recovery and recycling (R3) or other disposition of conventional ammunition, rocket motors and energetics. All strategic and tactical conventional weapons systems now require disposition planning and capability as part of their lifecycle.

This paper describes the facility, experiments, and technology development, and provides an overview of the results and how they apply to the goal of improving demilitarization activities.

Cooperative Effort

The facility and experiments are made possible by the combined efforts of many people from DoD and DOE organizations. Program management and funding originate from the Defense Ammunition Center and are coordinated for DOE by the Nevada Operations Office. Facility development and operations are carried out by Bechtel Nevada. Lawrence Livermore, Los Alamos and Sandia National Laboratories design and direct the experiments and develop technology for time-resolved measurements. Radian International LLC and the Harry Reid Center for Environmental Studies at the University of Nevada Las Vegas provide sampling and analyses for US Environmental Protection Agency (EPA) regulated materials.

Objectives

The first objective was to develop a facility for contained burn or detonation of full scale conventional items at a net explosive weight (NEW) that approaches typical service disposal amounts. Having a test area that could handle complete assets as-is eliminated the uncertainties of scaling from small amounts of bare explosive to 10,000 pounds NEW. It also measured the results of metal fragmentation, rather than estimating composition and amounts of metals that could exist as respirable or fallout components.

The second objective was to be able to measure all the products which were considered to have impacts to personnel, the environment or the facility safety factors. Products are contained in the chamber where mixing is good because of thermal convection and explosive injection, so the samples we take fairly represent this mixture.

The third objective was to determine time-resolved and -integrated parameters which could be used to evaluate and model the effects of alternative detonation or burn procedures. Some of these are pressure, temperature and gas composition. The time-integrated measures are valuable for endpoint factors, such as efficiency of carbon conversion, while time-resolved ones lead to better understanding of the detonation and burn processes and help to develop and validate detailed models. We used the tunnel tests to develop technologies for real-time measurements of aerosol size and composition and for gas composition. These new technologies may be transferred to open atmosphere tests, where the integrated measurements are more difficult because the products are diluted to a much greater degree than in the chamber.

The X-Tunnel facility

At the end of the 600 foot-long X-tunnel within NTS's Little Skull Mountain, is a mined chamber and containment barrier designed to withstand a 2000 pound TNT-equivalent detonation. A view of the facility is given in Figure 1. The chamber has dimensions of approximately 100 ft length, 50 ft width and 35 ft height, with a volume of 164,000 cubic feet.

The interior of the chamber is ashfall tuff deposited during volcanic activity ~15 million years ago. This natural surface is stabilized with rock bolts and covered with chain link fabric and a thin layer of steel-fiber-reinforced concrete to prevent catastrophic sloughing of the surfaces during manned operations. The barrier is designed to allow workers and equipment access to the chamber as well as provide the connections to the sampling systems. Before each test, the barrier is closed

and sealed so the chamber is leaktight to contain the products for sampling.

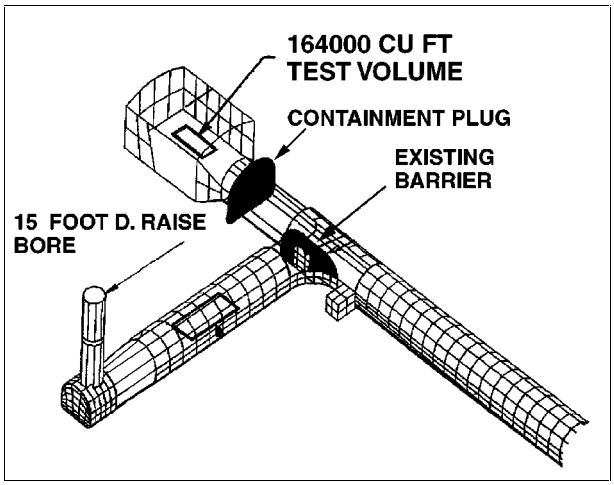

Figure 1. X-Tunnel and chamber at the DOE's Nevada Test Site.

Most analysts would prefer an inert surface for the containment chamber to rule out interactions between the products and the walls. In this case, the high cost of and potential for damage to an inert liner led to a compromise where three munitions tests would be identical and these results were expected to provide a measure of reproducibility and chamber backgrounds.

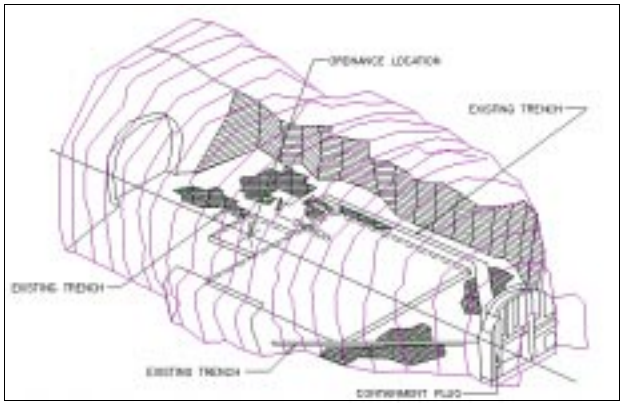
Figure 2. X-Tunnel Chamber in FY97.

A more detailed view of the chamber is shown in Figure 2. Several sampling systems are mounted on the containment plug, but are not shown. In the two years since it was first used, the concrete pads have been expanded to the sides and back-end of the chamber.

The Experiments

Two types of experiments have been performed at the X-Tunnel facility, detonation of projectiles and burn of rocket motors. Livermore was the lead for detonation tests and Sandia directed the burns.

Munitions tests

Detonation is the standard method of disposal for M107, 155-mm high explosive projectiles. Donor charges of C4 explosive sympathetically detonate the projectile. This process results in fragmentation and dispersion of the metal case and lifting lug, and conversion of the C4, Composition B and supplemental charge explosives[1] to several types of products.

In FY97 we adopted a graded approach to the experiments by starting with 6 projectiles, then two tests with 24 each and finally a 60 item shot. The NEWs totalled 110, 438, 439 and 1029 pounds. This staging allowed assessment of effects to the tunnel and gave experimenters opportunities to adjust equipment for increasing amounts of products. For the first two tests, the projectiles were placed on top of a 1" thick steel plate at the ordnance location given in Figure 2. These detonations forced the plate to move and fragment and excavated a crater which was too large to fill with new concrete. Subsequently, 3/4" gravel filled the hole and the projectiles were placed directly on this material.

The FY99 series included three tests of 24 M107 projectiles (439 lb NEW). Two experiments repeated the FY97 test (named

[1] C4=91 weight% RDX, 5.3% di(2-ethylhexyl)sebacate, 2.1% polyisobutylene, 1.6% motor oil.
Composition B=63 wt% RDX, 36% TNT, 1% wax.
Supplemental charge=98.5wt% TNT, 1.5% Barium Stearate

Beast) to obtain data for determining the reproducibility of the experiments and chamber response. The last FY99 test changed the placement of the projectiles from horizontal to vertical with respect to the chamber floor to examine whether critical parameters were more favorable in this alternative configuration.

Rocket Motor Tests

Following the munitions tests in FY97, double base and composite propellant in Nike and Improved Hawk rocket motors, respectively, were burned at low pressure after explosively rupturing the cases. The two Nike tests consumed the contents of 2 and 4 motors (1500 and 3000 lb NEW), and the Hawk test burned 2 (1294 lb NEW). The motors were chained to the large concrete pad to prevent damage to the chamber.

Measurements and Results

Physical parameters

Static and dynamic pressures, temperatures, accelerations in the ground and barrier, and relative humidity are measures of the physics and chemistry of the detonations and burns. These factors scale in ways that we understand, ie. with NEW and/or metal mass. Hence, we can also use them as validation points for models and as evaluation parameters for OB/OD procedures.

Generally these factors scaled with NEW within a type of munition or rocket motor. An example of this type of behavior is seen in Figure 3. The peak and falloff pressures increase with the number of items in the tests, 6 in Banshee, 24 for Polaris and Beast, and 60 in Colossus. However there is a significant difference between Polaris and Beast that may be related to the change from the steel plate to the gravel base. The two tests replicating Beast may help to explain this difference.

The rocket motor burns destroyed more energetic material than the munitions, and produced higher temperatures and pressures in the chamber. A series of thermocouples measured temperatures at different heights above the chamber floor in order to provide data on burn rate and heat transfer.

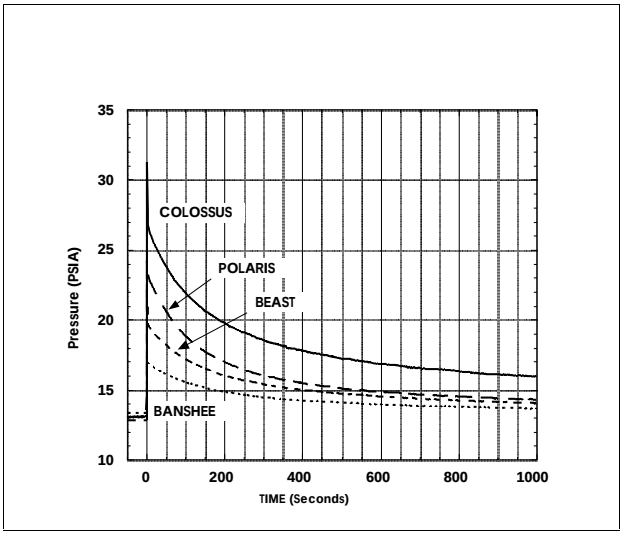

Figure 3. Static pressures of the FY97 munitions tests.

Gas composition

Gaseous products of explosive or propellant reactions are chiefly nitrogen, carbon monoxide (CO) and water. The atmosphere provides oxygen to convert the CO to carbon dioxide (CO_2). These gas concentrations can provide some of the important factors for evaluating demilitarization processes, such as the extent of carbon conversion and production of trace gases. Using the reactive material inventory and an assumption of complete combustion, we find that the gas compositions are within 15% of the expected values for both detonation and burn.

Typical data for these experiments is shown in Fig. 4. Acidic gases such as carbon dioxide and nitric oxide show peaks shortly after detonation and slowly decrease in

concentration thereafter. Gases such as oxygen, krypton, and carbon monoxide change concentration due to the detonation and remain at a constant volume fraction of the chamber gases until the chamber purge system is engaged.

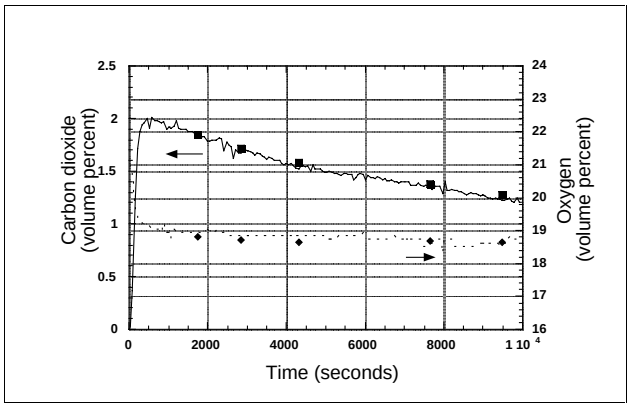

Figure 4. Carbon dioxide and oxygen by continuous monitoring (lines) and grab samples (symbols).

For the munitions, the CO_2 concentration is slightly lower than expected, indicating that incomplete combustion occurred. CO and some other incomplete combustion products, were also present. Overall conversion of the explosive carbon to gas products ranged from 85-94% for the FY97 tests.

The rocket motor burns converted more than 99% of the propellant carbon to gaseous products, with the remainder in incomplete combustion products.

Particulates

These experiments loaded the chamber atmosphere with particulate matter whose hazards may be regulated by Resource Conservation and Recovery Act, Environmental Protection Agency or Occupational Safety and Health Administration. The amounts of material in total and respirable size fractions were obtained from filters.

The total suspended particulate (TSP) amounts for munitions were in the range of hundreds of milligrams per cubic meter (mg/m^3). The respirable size fraction, < 10 microns, denoted PM_{10}, was in the range of tens of mg/m^3.

The rocket motor burns produced TSP levels of ~1200 mg/m^3. PM_{10} for Nike motors averaged 300mg/m^3, but the Hawk gave 1000 mg/m^3 in this smaller size fraction.

Metals

Environmentally regulated and non-regulated metals analyses from several of the sampling methods yielded data to assess the contributions from the test and chamber materials.

For munitions, metals detected in the residue and particulate samples were dominated by metals from the projectiles and concrete. Highest levels of 10-40 mg/m^3 iron and 30-90 mg/m^3 calcium reflect those sources respectively. There were no amounts of metals that exceeded current regulatory limits.

The higher weights of test materials in the rocket motor burns increased the metal mass of the residue and particulate samples. Highest results of ~300 mg/m^3 were from lead and aluminum, components of the propellants. There was some cross contamination because the walls and ceiling of the chamber were not cleaned between burns. Contributions from the chamber materials were not as significant as in the munitions tests because the burn process was not as damaging to the chamber.

Organic Compounds

Organic chemicals were measured by collecting grab samples followed by off-line analysis. Volatile organic compounds (VOCs) were determined by EPA Compendium Method

Technical Order (TO)-14 and 12 and semivolatile organic compounds (SVOCs) by a combination of EPA SW-846 Methods 0010 and 8270).

Emissions of EPA regulated materials from the munitions were found only in trace levels (<10 parts per million by volume, ppmv), and were more consistent than one would expect if scaling with NEW occurred. Differences between these experiments is probably a measure of experimental uncertainty or the level of reproducibility in the chamber.

Rocket motor burn levels were <100 ppmv. More compounds were found in the Nike samples than the Hawk, which may reflect the differences in composition of double base and composite propellant.

Item specific products

When analyses for specific compounds were needed, appropriate methods were added to provide this data. For example, results for HCN, which was about 2 ppmv for the munitions was 10x higher for the Nike motors. Rocket burns generated lead, asbestos and chlorine-containing species, such as hydrogen chloride and dioxins. These measurements addressed toxic hazards to personnel and the environment.

Residue samples

After each experiment, material was collected from the floor of the chamber and from metal plates suspended from the chamber walls. We obtained analyses for metals, energetics[2] and SVOCs.

The only energetic detected from detonations was 41 microgram RDX /kilogram residue in the 6 item test. Of the burn tests, ~10 milligram RDX/kilogram residue (ppm) was measured in the Nike residues, and sub-ppm HMX and two other compounds from the Hawk samples.

Chamber materials samples

Metals were quantitated in samples of the concrete, shotcrete, rock, aggregate and soil from the X tunnel chamber. These results were used as background levels to correct results from the tests.

Technology Development

The most challenging objective of these experiments is the one of collecting data on a time-scale short enough to provide details of demilitarization processes. Both types of experiment have particulate and gaseous emissions which we employ to evaluate the effectiveness, efficiency and economy of the procedure.

Particulate sampling has traditionally been performed over times that are long compared to settling times, so dynamic information is lost. To recover this data, we have developed an aerosol sampler that can provide size and time history.

Gas analysis by laser techniques is able to deliver results on the sub-second time scales characteristic of explosive and burn processes. We developed a laser system to measure the concentrations of some of the gases at two locations within the chamber.

Aerosol Sampler

The Los Alamos Aerosol Sampling System (LAASS) was used to measure aerosol concentrations and collect aerosol samples after the detonation by drawing aerosol-laden gas through the barrier into two parallel sampling

[2] Energetics:
RDX= Hexahydro-1,3,5-trinitro-1,3,5-triazine.
HMX=Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine.

systems. One system (impactor) collected aerosol samples from 10 to 0.1 µm in aerodynamic diameter and measured mass concentrations (µg/m^3) in real time. The other system (streaker) collected three size fractions, > 10 µm, 2.5 - 10 µm, and < 2.5 µm. The latter two size fractions are collected on rotating substrates thereby providing a time history of the aerosols present in the test chamber. The streaker samples are analyzed using Proton-Induced X-ray Emission (PIXE) Spectroscopy to determine the aerosol elemental composition for elements of atomic number greater than sodium. Size distribution and elemental concentration data were typically obtained from 10 minutes to 1 hour after the detonation.

Figure 5 displays a time history of the mass loads for two different size fractions. We see that just after detonation, both sizes have the highest amount of material. As time increases, material settles out and the aerosol concentration drops. This type of information helps to develop and validate aerosol transport models.

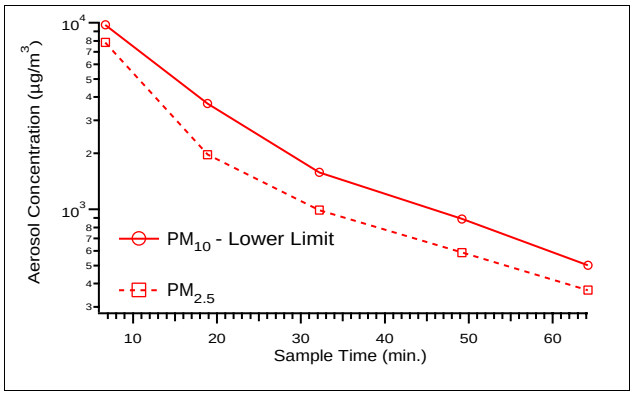

Figure 5. Beast impactor aerosol concentrations.

The LAASS operated successfully for all of the tests and obtained data on aerosol size distributions and elemental concentrations for the small particle (< 10µm) fraction of the aerosol population.

Tunable Diode Laser

The goal of the Sandia tunable diode laser (TDL) instrumentation was to obtain time-resolved analyses of reactive, hazardous gases as they evolve in the X-tunnel test chamber. Temporal evolution of these species at two different locations in the chamber would provide an indication of completeness of combustion and mixing. One of interest is hydrogen cyanide (HCN) since it is very difficult to measure reliably with conventional techniques.

During the test series, measurements of carbon monoxide, carbon dioxide and water were also performed. For these experiments, optical line-of-sight absorption measurements are made at two different locations in the X-tunnel test chamber, in the side and floor. Specially designed, shock-hardened enclosures are protected from blast debris at each measurement location. The lasers and signal processing electronics are housed in a compact instrumentation package outside the tunnel.

TDL succeeded in performing time-resolved measurements of carbon dioxide and water, but did not observe evidence for hydrogen cyanide. Grab samples did show the concentration of hudrogen cyanide to be very low and below the sensitivity of the TDL. Carbon monoxide was observed just at the TDL detection limit.

The largest challenge with the TDL equipment proved to be maintaining adequate laser transmittance under conditions of high dust-loading. The transmittance loss is due to a combination of dust in the sample volume and dust adhering to the windows. The highest probability of detecting transient molecular species (e.g. CO, HCN) is just after the detonation, before combustion proceeds very far, and before significant dispersal occurs. However, this is also the time period of highest

pressure and the most severe dust-loading. Both of these features combine to decrease the sensitivity of the measurements. Laser transmittance during the critical time period of a demil event is likely to be the limiting factor for future application of laser-based measurements.

Conclusions

Substantial progress has been made in achieving the objectives described at the start of this paper. The facility is complete and operational, with flexibility to characterize most items in the demilitarization portfolio. We are determining the reproducibility of tests and backgrounds in the chamber. Time-resolved and time-integrated measurements from both new and established technologies have provided several factors which can be used to evaluate and model the effects of existing and alternative detonation or burn procedures.

Munitions

The data from the detonations were compared to the expected levels based on dynamic and thermodynamic considerations. In general, the results increased with the NEW of the tests, but trends for some types of results were not uniform. The variations or deviations may be due to: normal sampling and analytical variability; differences in the support platform for the projectiles; or, real differences in detonation chemistry. We shall be able to resolve some of these questions when the FY99 results are available and determine which factors are most important for characterizing the effectiveness of DoD OD processes.

Rocket Motors

The extensive suite of measurements obtained from these tests includes chemical kinetic data that define important features of time-dependent gas species evolution in the combustion clouds produced by burning propellants. In addition, the thermodynamic data define the environmental conditions produced by the intense combustion processes in the test chamber. These data are the key elements needed to understand the contained burn process more completely. It is necessary to combine that understanding with the time-averaged and time-resolved gas species and particulate concentration data in order to develop improved operational procedures for DoD OB demilitarization sites. These improved procedures could reduce the environmental impacts of future OB operations.

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